

SEARCHING FOR GRAVITATIONAL LENSES IN THE DISTANT UNIVERSE

Andrew W. Blain

Cavendish Laboratory, Madingley Road, Cambridge, CB3 0HE, UK.

E-mail: awb@mrao.cam.ac.uk; Tel: +44 1223 337234; Fax: +44 1223 354599.

ABSTRACT

FIRST has the ideal combination of sensitivity and angular resolving power to determine the bright counts of galaxies over a large area of sky in the submillimetre (submm) waveband. Important information about the evolution of galaxies at moderate redshifts will be provided by the analysis of these counts, and the effects of gravitational lensing will make the counts even more significant for observational cosmology. This paper describes the flux and surface densities of lensed galaxies in the submm waveband and explains how *FIRST* could be used to discover several tens of lenses. The *Planck* and *FIRST* missions are very well suited to cooperate in this programme, and together could compile a larger sample of several hundred lenses. *FIRST* will be able to detect the signal due to the Sunyaev–Zel’dovich (SZ) effect in a large sample of clusters. These observations could also be used to investigate submm-wave lensing by clusters, and to infer the properties of the population of faint distant galaxies.

1. INTRODUCTION

The submm-wave flux density of a distant ($z > 1$) dusty star-forming galaxy or quasar with a fixed luminosity is predicted to be almost independent of redshift [Ref. 1, 2]. The continuing development of submm-wave cosmology is motivated by this flux density–redshift relation and the corresponding steep counts. However, there is another counter-intuitive feature of the population of distant galaxies in the submm waveband – the fraction of gravitationally-lensed galaxies is expected to be up to three orders of magnitude larger in a sample of galaxies that is selected in this waveband as compared with one selected in any other waveband [Ref. 3, 4]. The largest excess of lenses is expected at the flux density at which the submm-wave counts begin to rise steeply above the Euclidean slope. Gravitational lensing leads to a similar enhancement of the surface and flux densities of distant galaxies in the fields of clusters, which can be exploited to investigate the evolution of the population of faint background galaxies in submm-wave observations of the SZ effect [Ref. 5].

A density parameter $\Omega_0 = 1$, a cosmological constant $\Lambda_0 = 0$ and a value of Hubble’s constant $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are assumed throughout unless otherwise stated.

2. GRAVITATIONAL LENSING

The properties of both the population and individual appearance of distant galaxies can be modified significantly by the gravitational lensing effect of foreground masses [Ref. 6], whether galaxies, clusters or structures on larger scales [Ref. 7]. Gravitational lensing has been studied in most detail in the optical and radio wavebands, in which faint distant galaxies can be observed with sub-arcsecond resolution [Ref. 8, 9]. However, there are excellent prospects for extending these studies into the submillimetre waveband, using both high-resolution and wide-field observations.

The concept of magnification bias provides a useful way of describing the effects of lensing on a population of distant galaxies [Ref. 8, 10]. If the surface density of galaxies with flux densities larger than S_ν per unit redshift at redshift z is $n(S_\nu, z)$, then magnification by a factor A due to gravitational lensing would predict a modified count,

$$n'(S_\nu, z) = A^{-1} n[S_\nu A^{-1}, z]. \quad (1)$$

If $n \propto S_\nu^\alpha$ locally, then $n' \propto S_\nu^\alpha A^{-(1+\alpha)}$. The magnification bias n'/n is hence given by $A^{-(1+\alpha)}$: for $\alpha < -1$ the surface density of galaxies is increased and the magnification bias is positive; for $\alpha > -1$ the surface density of galaxies is decreased and the magnification bias is negative. Magnification bias was first discussed in the context of samples of bright quasars; however, counts at faint flux densities in the submm waveband are uniquely steep, with $\alpha = -3$ or less, and so the magnification bias for faint galaxies in this waveband is expected to be very significant [Ref. 4, 11]. In the case of lensing by clusters of galaxies, the magnification A is a function of position within the cluster, but the effect of magnification bias still applies.

The magnification distribution as a function of redshift, $F(A, z)$ can be derived from the mass distri-

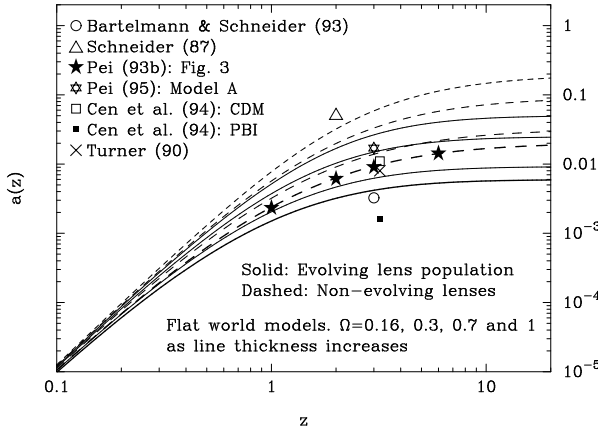


Figure 1: The probability of galaxy–galaxy lensing as a function of redshift, which can change significantly if $\Lambda \neq 0$ or the lens population evolves. The lensing optical depth $\tau \simeq a/8$. For references see [Ref. 4].

bution of galaxies [Ref. 12, 13], and takes the form $a(z)A^{-3}$ if A is large. A range of estimates of $a(z)$, which are calculated in several different world models and both evolving and non-evolving models of the distribution of lensing masses, are presented in Fig. 1. The world models are all flat, with $\Omega_0 + \Lambda_0 = 1$, but include different density parameters Ω_0 . The evolving mass distribution of the population of lensing galaxies is derived using the Press–Schechter formalism for structure formation by hierarchical clustering [Ref. 14], in which galaxies typically become smaller and more numerous as redshift increases. The probability of lensing is expected to increase as the size of the cosmological constant increases, and is expected to be smaller in the evolving model as compared with the non-evolving model. The magnification distribution can be used to predict the surface density of lensed galaxies with flux densities greater than S_ν ,

$$N_L(S_\nu) = \int_0^{z_0} \int_2^\infty \frac{F(A, z)}{A} n \left[\frac{S_\nu}{A}, z \right] dA dz. \quad (2)$$

The count of unlensed galaxies,

$$N_U(S_\nu) = \int_0^{z_0} n(S_\nu, z) dz. \quad (3)$$

3. LENSING BY FIELD GALAXIES

Models of the population of distant dusty star-forming galaxies [Ref. 15] can be used to predict n (Equation 1), and hence to derive counts of both lensed and unlensed galaxies (Equations 2 & 3). The form of $a(z)$ assumed in the calculation of the lensed counts is normalised to match the predictions of [Ref. 13], that include a total density in compact objects $\Omega_G = 0.16$.

Multi-waveband studies of the evolution of galaxies and active galactic nuclei (AGN) [Ref. 16, 17, 18 19] indicate that the increase in both the global star-formation rate and the luminosity density of AGN is consistent with pure luminosity evolution of the form $(1+z)^3$ out to $z \sim 2$. Three models of galaxy evolution are discussed here; A, B and C. They are all normalised to match the low-redshift luminosity function of *IRAS* galaxies [Ref. 20] and undergo pure $(1+z)^3$ luminosity evolution out to a redshift $z_{\max} = 2$, but include different forms of evolution at larger redshifts $z < z_0$. Models A and B include no further luminosity evolution at $z > z_{\max}$ and values of $z_0 = 5$ and 2 respectively. Model C includes negative luminosity evolution of the form $(1+z_{\max})^3 t(z)/t(z_{\max})$ for $z_{\max} < z \leq z_0 (= 10)$; $t(z')$ is the cosmic epoch at redshift z' .

The counts predicted in all three models are compared in Fig. 2(a). Estimates of the lensed counts are calculated for both the evolving and non-evolving mass distributions of lenses; the surface density of lensed images is predicted to be smaller in the evolving model. The counts predicted in different world models (Fig. 1) are compared in Fig. 2(b). A non-zero cosmological constant both increases the predicted surface density of lensed galaxies, due to an increased probability of lensing, and decreases the counts of unlensed galaxies, due to a smaller volume element at large redshifts as compared with an Einstein–de Sitter model. The wavelength dependence of the counts is presented in Figs 2(c) & 2(d). The 90- μ m counts take a similar form to those expected in the optical or radio wavebands, but the relative density of lensed and unlensed galaxies in the submm waveband is expected to be about two orders of magnitude larger as compared with other wavebands. The surface density of both lensed and unlensed galaxies is expected to decrease as the wavelength of observation increases.

4. A *FIRST* LENS SURVEY

FIRST will provide a unique facility for submm-wave cosmology and will discover a host of new sources at large redshifts – these will be valuable targets for future ground-based submm-wave interferometer arrays and 8-m telescopes operating in the optical/near-infrared waveband. Unaffected by atmospheric absorption, *FIRST* offers a unique capability to survey large areas of sky: large millimetre arrays [Ref. 21, 22] will provide sub-arcsecond resolution and sub-mJy sensitivities, but only in relatively small fields. *FIRST* would be very useful for observing molecular and fine-structure lines from known objects, which would otherwise be blocked by the atmosphere; however, the much larger antenna areas

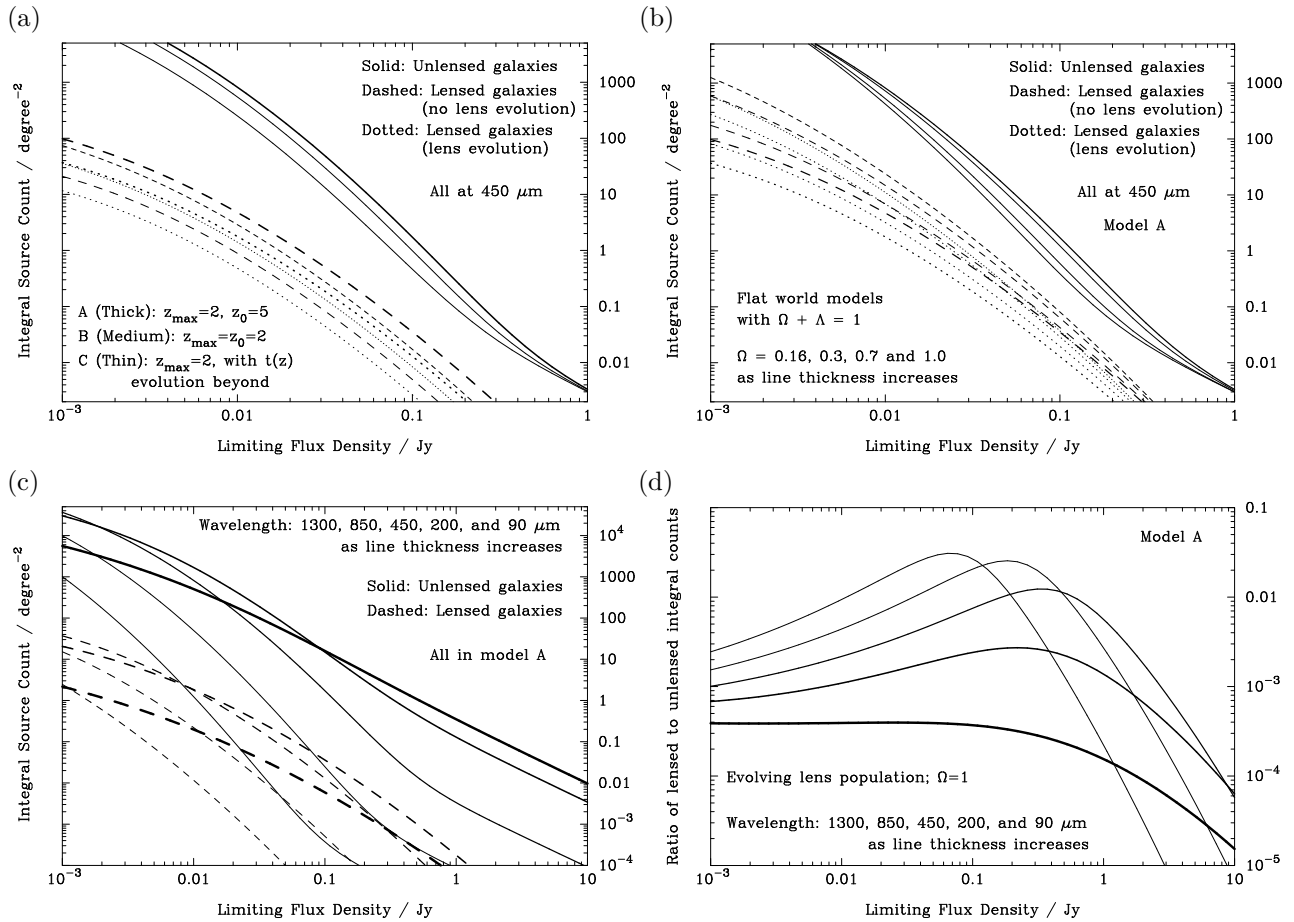


Figure 2: The counts of lensed and unlensed field galaxies expected in a range of galaxy evolution scenarios (a) and world models (b). The wavelength dependence of the counts is compared in (c) and (d).

of ground-based submm telescopes would give them a significant advantage over *FIRST* for conducting blank-field surveys [Ref. 3].

Estimates of the number of lensed and unlensed galaxies that could be detected in a 0.2-year *FIRST* survey at 450 μm are presented in Fig. 3, based on a model of telescope performance [Ref. 23] and the counts derived above. Estimates of the numbers of galaxies that could be detected in the extreme cases of a confusion-limited survey and an all-sky survey are listed in Table 1; in the case of an all-sky survey the sensitivities of *Planck* [Ref. 24] are assumed. All these estimates are derived under the assumptions of an evolving population of lensing galaxies, galaxy evolution model A and an Einstein-de Sitter world model. The results can be scaled to match other scenarios using the counts in Fig. 2, and the predicted number of lenses could be increased by a factor of about 5 without violating other observational constraints.

Between about 0.1 and 1% of the sources detected in a *FIRST* survey are expected to be lensed by a foreground galaxy. At a wavelength of 850 μm the sur-

face density of detectable sources is expected to be rather small, despite a relatively large ratio of lensed to unlensed galaxies. Hence, the only practical wavelengths for a lens survey are 200 and 450 μm . The number of lensed galaxies expected at these wavelengths depends rather weakly on the limiting flux density, as shown in Fig. 3. A 450- μm survey lasting 0.2 years at a flux density limit of less than 50 mJy would yield about 40 and 16 lenses at signal to noise ratios of 5- and 3- σ respectively, amongst of order 10^4 unlensed galaxies. This potential sample of systematically-selected lenses is comparable in size to the existing set of known lenses. Of course, the counts of unlensed galaxies in the submillimetre/far-infrared waveband would also be accurately determined in such a survey, leading to a more complete understanding of the evolution of the global star-formation rate at moderate redshifts.

An all-sky *Planck* survey would detect of order 500 lensed galaxies, Table 1. However, *Planck*'s 4-arcmin angular resolution is too coarse for rapid follow-up observations using ground-based telescopes, and the survey would detect a very large number – of or-

Table 1: σ_{cirrus} [Ref. 25] and σ_{conf} are the cirrus and faint source confusion noise expected in a *FIRST* survey respectively, assuming that the mean galactic background intensity $I_{100\mu\text{m}} = 5 \text{ MJy sr}^{-1}$ and σ_{conf} is the flux density of galaxies with a surface density of 0.03 beam^{-1} . σ_{sky} is the sensitivity of a *Planck* all-sky survey [Ref. 24] and \dot{A}_{conf} is the rate of sky coverage that *FIRST* could achieve at a $5\text{-}\sigma$ limit of σ_{conf} . N_{conf} and N_{sky} are the number of $5\text{-}\sigma$ sources expected in a 0.2-year confusion-limited survey and a *Planck* all-sky survey respectively.

λ / μm	σ_{cirrus} / mJy	σ_{conf} / mJy	σ_{sky} / mJy	\dot{A}_{conf} / $\text{deg}^2 \text{ day}^{-1}$	N_{conf}		N_{sky}	
					lensed	unlensed	lensed	unlensed
200	0.41	9.4	150	0.10	15	1.4×10^4	650	2.4×10^5
450	0.51	14	100	0.22	16	6.6×10^3	560	7.1×10^4
850	0.36	7.6	80	0.023	0.7	180	40	2.3×10^3

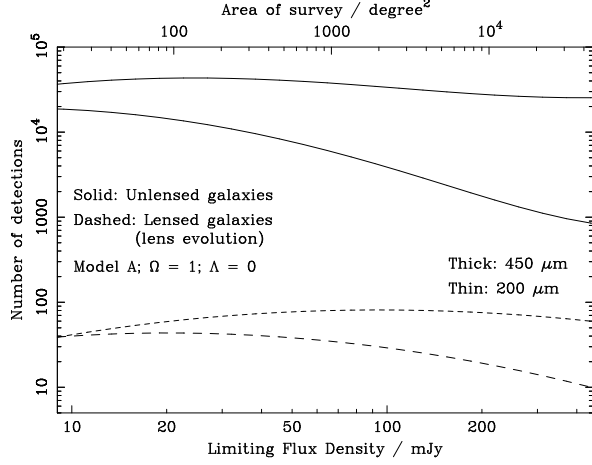


Figure 3: The number of $3\text{-}\sigma$ detections expected in 0.2-year *FIRST* surveys at 200 and $450\mu\text{m}$.

der 10^5 – unlensed galaxies at wavelengths of 200 and $450\mu\text{m}$. A total of only about 2300 candidate sources are expected at a wavelength of $850\mu\text{m}$, and so *FIRST* could determine more accurate positions and flux densities for these galaxies in a short time – several tens of hours. However, this would not be possible for the much larger number galaxies detected at either 200 or $450\mu\text{m}$. Despite this, the rewards from being able to sift through this large sample and select the lensed galaxies would be very considerable, and it is difficult to see how such a large sample of lenses could be compiled in any other waveband. Tens or hundreds of gravitational lenses could be detected in the submm waveband using *FIRST* and *Planck*, but how efficiently could these most valuable objects be separated from distant unlensed galaxies?

The magnification distributions expected at three limiting flux densities at a wavelength of $450\mu\text{m}$ are shown in Fig. 4. The distribution is tilted towards larger magnifications at larger limiting flux densities; however, even in the deepest survey, most lensed galaxies would be expected to experience magnifications of order 4, and so a high-resolution image of a

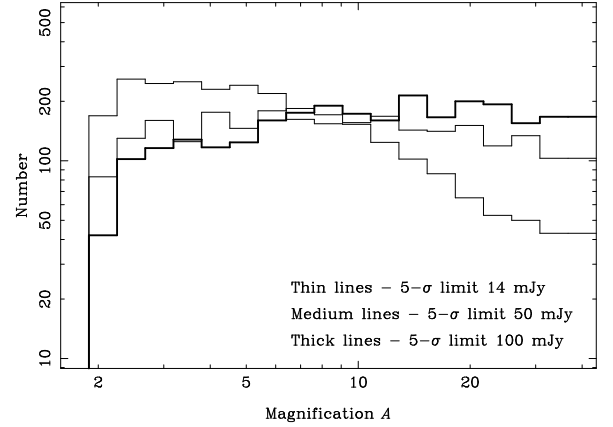


Figure 4: The magnification distributions expected in $450\text{-}\mu\text{m}$ *FIRST* surveys at different depths.

lens would be expected to show either several bright components, or to be significantly larger as compared with an unlensed galaxy at the same redshift. Hence, lensed and unlensed galaxies should be readily distinguishable in observations using large ground-based interferometer arrays. At a wavelength of $850\mu\text{m}$ these telescopes could detect a 10-mJy source at a signal-to-noise ratio of about $60\text{-}\sigma \text{ beam}^{-1}$ in a 1-minute integration [Ref. 21]. This sensitivity and the 0.1-arcsec resolution of a large array should together be sufficient to allow any signs of lensed structures to be detected. Hence, a concerted and carefully-scheduled programme of follow-up observations using such an array could select the lensed sources in a sample of 10^4 candidates in a few hundred hours.

Colour-magnitude and colour-colour diagrams for the simulated results of a confusion-limited and all-sky survey are presented in Fig. 5. These results suggest that such diagrams could be used to pre-select and order detected sources for ground-based imaging: lensed galaxies are found exclusively at large redshifts; and, if the dust temperature in star-forming galaxies is correlated with their luminosity, then lenses would be expected to have redder colours

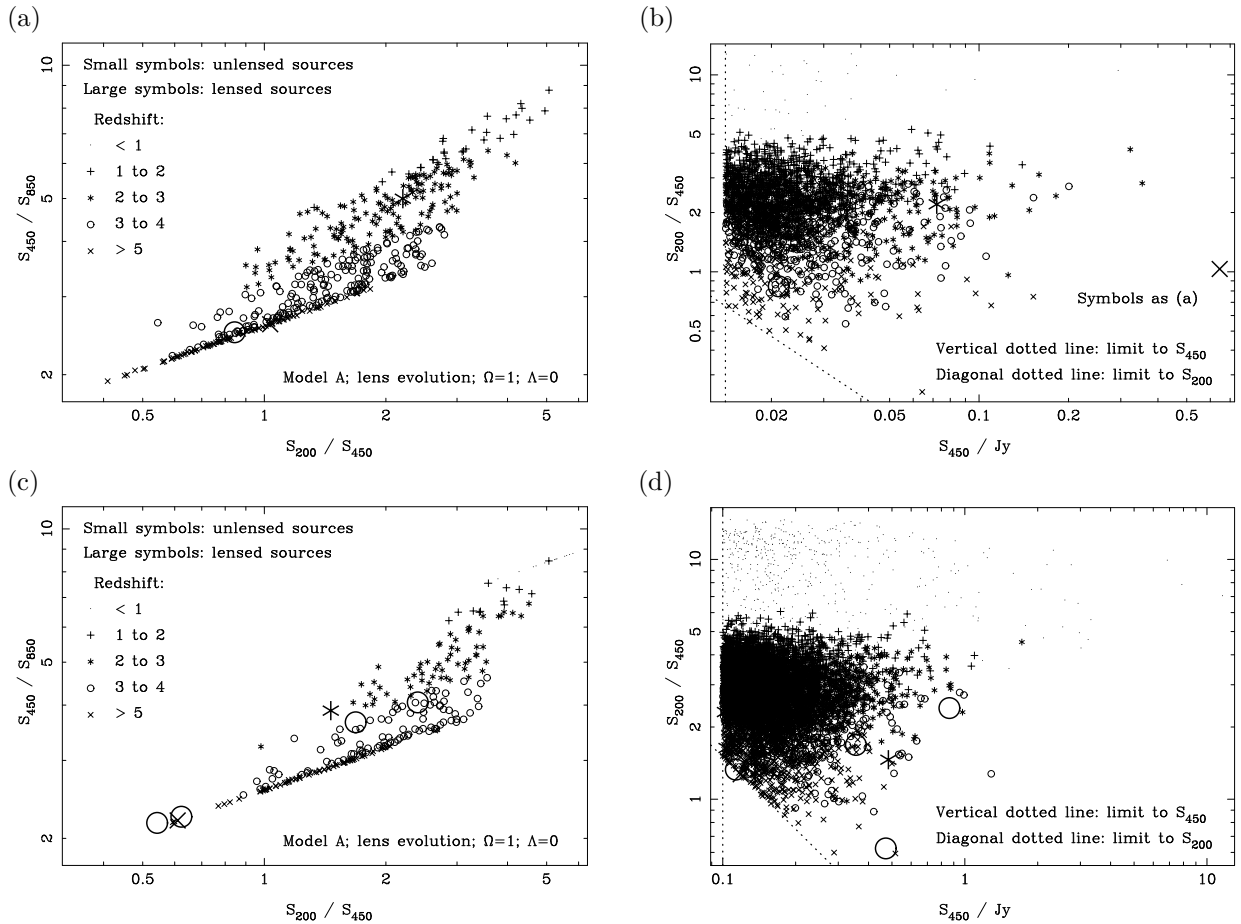


Figure 5: Colour-colour and colour-magnitude diagrams of typical samples of lensed and unlensed galaxies selected at $450\mu\text{m}$ in a confusion-limited [(a) & (b)] and all-sky [(c) & (d)] survey. Careful selection of lensing candidates using these diagrams could increase the selection efficiency of a lens survey.

as compared with unlensed galaxies at the same flux densities. Careful pre-selection of targets based on their colours in the submm waveband could reduce the size of the sample by a factor of a few, but high-resolution ground-based imaging of all the remaining candidates would still be required in order to select lenses unequivocally.

The lensed galaxies detected in a *FIRST* survey would of course be subject to a detailed multi-waveband observing campaign. The properties of both the population and individual appearance of lenses in the sample would then be analysed in order to measure cosmological parameters and investigate the evolution of large-scale structure.

5. CLUSTERS

Distant galaxies are also lensed by foreground clusters. In fact, the lensed images of distant galaxies are expected to be the brightest sources of submm-wave radiation in the field of a cluster of galaxies on arcsecond-scales [Ref. 11]. These images could not

be resolved using *FIRST*, but their presence would be expected to increase the level of source confusion noise in the direction of the cluster – by a factor of about 3 as compared with observations in the field [Ref. 26, 27]. The properties of this source confusion noise could be used to infer the form of evolution of faint galaxies in the submm waveband. Observations of a large sample of clusters would be required in order to investigate this effect; however, such a series of observations is already planned to investigate another important feature of clusters in the submm waveband – the SZ effect [Ref. 5, 28].

The depth of a blank-field *FIRST* survey is limited by source confusion to flux densities of about σ_{conf} (Table 1), at which clusters with y -parameters greater than about 5×10^{-5} and 5×10^{-4} would be detectable at a signal to noise ratio of $5\text{-}\sigma$ at wavelengths of 850 and $450\mu\text{m}$ respectively. The surface density of detectable clusters is expected to be about 10 and 0.3deg^{-2} at these wavelengths respectively [Ref. 29]. A cluster would hence be detected between every 5 and 10 days in a confusion-limited survey, a detec-

tion rate comparable to that expected for lensed field galaxies.

Source confusion is expected to be much less significant in the mm waveband [Ref. 27, 30], and so a *Planck* mm-wave all-sky survey has the potential to detect about 10^4 clusters with $y > 8 \times 10^{-5}$. These clusters would provide valuable targets for pointed *FIRST* observations, to investigate both the effects of lensing discussed above and the submm-wave SZ effect [Ref. 5].

SUMMARY

FIRST, especially in conjunction with the *Planck* mission, has the potential to detect and investigate the gravitationally-lensed images that are formed by both foreground galaxies and clusters.

i) The fraction of galaxy–galaxy lenses that could be detected in a *FIRST* survey depends on the properties of distant dusty galaxies and quasars, the observing wavelength and the flux density limit. It is expected to increase at longer wavelengths, and to be largest at the flux density at which the slope of the submm-wave counts begins to steepen at any particular wavelength. The surface density of detectable galaxies decreases at longer wavelengths, however, and is expected to be too small to allow a practical *FIRST* survey at a wavelength of $850\,\mu\text{m}$. Several tens of lenses could be detected in surveys at wavelengths of 200 and $450\,\mu\text{m}$; several tens of thousands of unlensed galaxies would also be detected, typically at moderate redshifts. First, submm-wave colours measured by *FIRST*, and secondly follow-up observations of suitable candidates using ground-based millimetre interferometer arrays and 8-m telescopes in the optical/near-infrared waveband would allow the lensed galaxies to be identified and studied further. The counts of unlensed galaxies could be used to constrain the evolution of the star-formation rate at moderate redshifts.

ii) Several hundred lensed galaxies, and about 10^5 unlensed galaxies, could be detected in a *Planck* all-sky survey at coarser resolution. Accurate flux densities and sub-arcminute positions for the most promising of these candidates could be obtained using *FIRST*, before similar follow-up observations.

iii) Several massive clusters could be detected due to their Sunyaev–Zel’dovich signal in a *FIRST* lens survey. Observations of a large sample of clusters, chosen from both those in pre-existing catalogues and the results of *FIRST* and *Planck* surveys, could be used to investigate the effects of lensing by clusters on the population of faint background galaxies in the submm waveband. These galaxies would otherwise be inaccessible to *FIRST*.

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